

BEST AVAILABLE COPY

# TRANSISTOR CIRCUIT THEORY AND DESIGN

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To  
Edythe,  
Virginia  
and  
George

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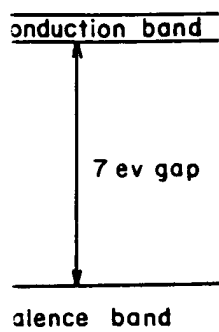
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## SEMICONDUCTOR PHYSICS

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**Example 1.6.** A material has a forbidden gap between the valence band and the conduction band of 2.58 ev. The constant  $A$  in Eq. (1.3) is  $10 \times 10^{16}$ . Find the number of current carriers available at room temperature ( $300^\circ \text{K}$ ).

**Solution:** From Eq. (1.3), the number of free electrons is

$$n_i = (10 \times 10^{16})(300^{3/2})e^{-2.58/(2 \times 0.0258)} \\ = 5.18 \times 10^{20}/e^{50} = 10^{-1}$$

or one electron and one hole for each ten cubic centimeters.

**Problem 1.9.** Find the resistivity of the material in Ex. 1.6 if  $\mu_n = 4000 \text{ cm}^2/\text{volt-sec}$  and  $\mu_p = 2000 \text{ cm}^2/\text{volt-sec}$ . (Ans.  $1.045 \times 10^{19}$ )

**Problem 1.10.** Find the resistivity of the material in Ex. 1.6 when the temperature is increased to  $2000^\circ \text{K}$ .

## 1.6. SEMICONDUCTORS WITH IMPURITIES

The resistivity of a semiconductor can be drastically reduced by the addition of small amounts of certain types of impurities. This is called doping. Impurities added to silicon and germanium are usually pentavalent (five valence electrons) or trivalent (three valence electrons). When a relatively small number of antimony atoms (five valence electrons) is added to germanium, four of the five electrons enter the covalent bond. The fifth valence electrons on each pentavalent atom is loosely attached to the atom. In terms of energy, these electrons occupy a state located very close to the bottom of the conduction band, as shown in Fig. 1.8a. An energy of only 0.01 ev is required to raise the fifth electrons into the conduction band, whereas 0.69 ev is required to break the covalent bond and elevate any of the other electrons into the conduction band. At room temperature, almost all of the impurity atoms supply one current carrier each.

The addition of small amounts of pentavalent impurities to silicon or germanium produces N-type semiconductor material. Because they add electrons to the conduction band without adding holes in the valence band, pentavalent impurities are often called "donors."

The addition of trivalent impurities produces P-type semiconductor material. Trivalent impurities are often called "acceptors," because they add holes in the valence band without adding free electrons in the conduction band. The three valence electrons of a trivalent impurity may enter the covalent bond. Since four electrons should be contributed by each atom to complete the covalent "octet," the bond is not complete. In

effect, a hole is produced. If an electron should fall into this hole, it will be bound tightly into the covalent bond, even though the impurity atom then has an extra electron or a net negative charge. In terms of conduction, the addition of trivalent impurity atoms creates unfilled energy levels close to the filled valence levels, as shown in Fig. 1.8b. Thermal energy available at room temperature enables the valence electrons from other atoms to move into these empty states. When this happens, empty states are available in the valence band, and the conduction of current can take place in the valence band with holes acting as current carriers.

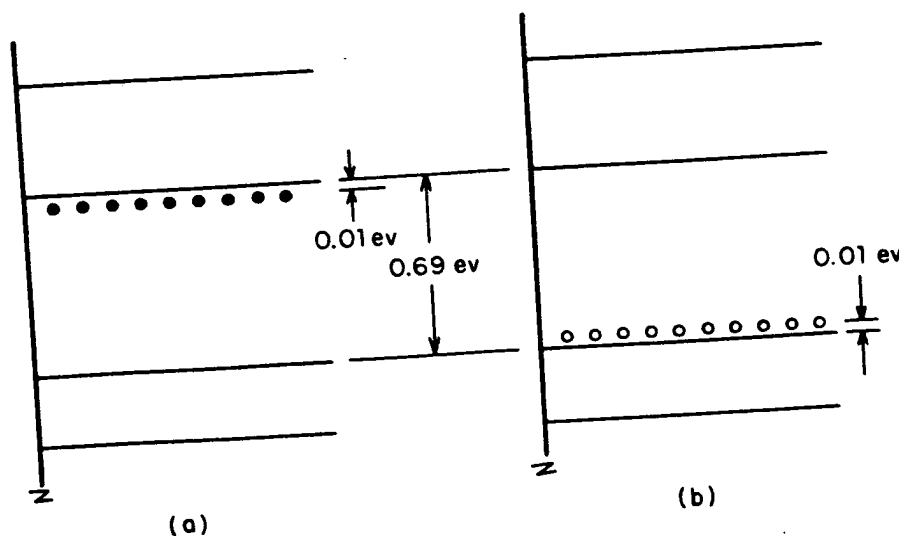


Fig. 1.8. Energy states for germanium doped with (a) pentavalent and (b) trivalent impurities.

A comparison of a cubic centimeter of intrinsic, P-type, and N-type semiconducting material is summarized below:

1. Each block is charge neutral, because each atom in the block was charge neutral when the solid was formed.
2. Intrinsic material has an equal number of electrons in the conduction band and holes in the valence band.
3. P-type material has fewer electrons, and N-type material has more electrons in the conduction band than holes in or near the valence band.
4. With equal temperature values and light doping, the product of the number of holes and conduction electrons is the same in all three

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cases. This product is approximately  $5.7 \times 10^{26}$  for germanium and  $2.3 \times 10^{20}$  for silicon at  $300^\circ \text{K}$ . We may conclude that P-type material has more holes and fewer free electrons than intrinsic material and that N-type has more free electrons and fewer holes than intrinsic material.

5. The mobility constants vary with the degree of doping. For example, in silicon, the following  $\mu$  values have been measured ( $\text{cm}^2/\text{volt-sec}$ ).

Doping atoms/ $\text{cm}^3$	N-type		P-type	
	$\mu_n$	$\mu_p$	$\mu_n$	$\mu_p$
$1 \times 10^{15}$	1380	460	1280	460
$5 \times 10^{15}$	980	390	870	410
$1 \times 10^{16}$	830	360	720	390
$2 \times 10^{16}$	700	315	560	370

A comparison of these values with those for intrinsic silicon may explain why the literature has many different values for the mobility constants.

6. The generation rate for electron-hole pairs is approximately the same for both intrinsic and doped semiconductors.

**Example 1.7.** Find the average number of holes and electrons in a cubic centimeter of silicon at  $300^\circ \text{K}$  if the sample is doped with one impurity donor atom for each  $10^7$  intrinsic atoms.

**Solution:** Silicon contains approximately  $5 \times 10^{22}$  atoms per cubic centimeter. Therefore,  $5 \times 10^{15}$  impurity atoms are added to the sample in obtaining the desired doping. Assuming that each impurity atom contributes one electron, then the total number of electrons is approximately the sum of the intrinsic and donor electrons or

$$n_t = n_i + n_d \approx n_d = 5 \times 10^{15}$$

The number of holes is

$$p_t \approx \frac{n_i^2}{n_t} = \frac{2.3 \times 10^{20}}{5 \times 10^{15}} \approx 4.6 \times 10^4$$

This last number is smaller than that for intrinsic silicon because, with many more electrons present, the probability of recombination is greater.

**Problem 1.11.** Find the resistivity of the sample of silicon in Ex. 1.7. Assume that  $\mu_n = 1135$  and  $\mu_p = 410 \text{ cm}^2/\text{volt-sec}$ . (Ans. Approx. 1.1 ohm-cm)

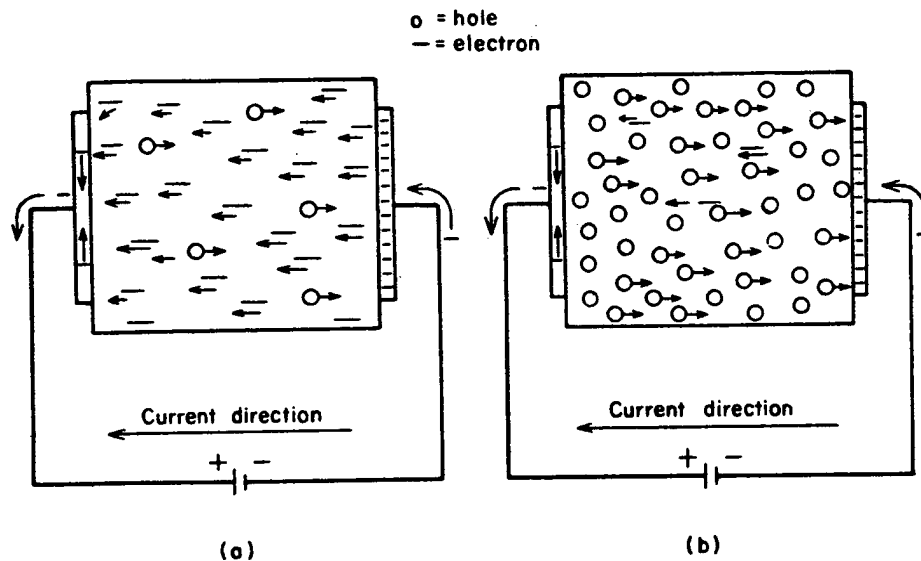


Fig. 1.9. Current flow by the mechanism of drift in an impurity semiconductor: (a) N-type and (b) P-type.

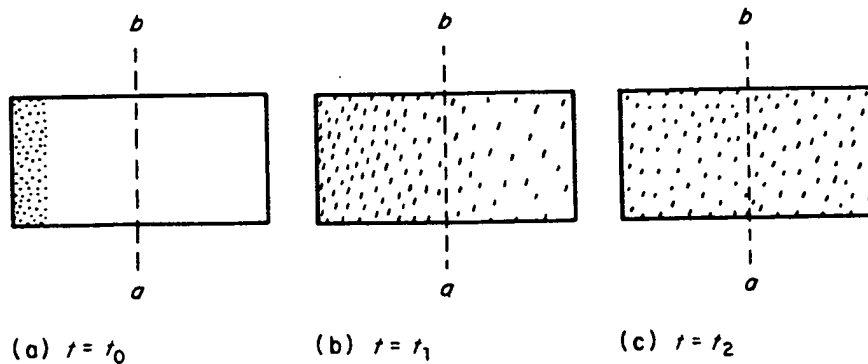


Fig. 1.10. Current flow by diffusion of carriers from an area of high concentration to an area of low concentration: (a) initial distribution; (b) distribution a short time later; (c) eventual distribution.

**Problem 1.12.**  
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## 1.7. DIFFUSION

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[§1.7]

**Problem 1.12.** Find the current in the same sample cube of doped silicon when 0.1 volt is applied to opposite faces of the cube. What part of this current is carried by holes?

As indicated in these examples, N-type semiconductors will have a high concentration of free electrons and a negligible number of holes moving randomly throughout the crystal structure. If suitably designed metal electrodes are attached to the crystal and if a voltage is applied, a net drift toward the positive terminal will be superimposed upon the random electron motion, as shown in Fig. 1.9a.

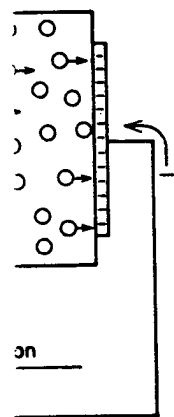
Holes are the majority carriers in P-type semiconductors. When a voltage is applied across the crystal, holes that are in random thermal motion drift toward the negative electrode and are annihilated by free electrons in the metal electrode. The uncovered negative, immobile ions near the positive terminal force electrons into the metal electrode; i.e., holes are injected into the crystal at the positive electrode. Thus, the crystal remains electrically neutral. It is significant to notice that, even though holes carry the current in the P-type semiconductor, the current flow in the electrodes and connecting wires consists of electron movement.

### 1.7. DIFFUSION CURRENT

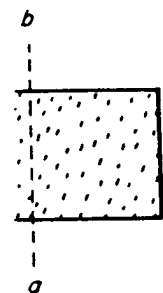
The previous sections were concerned with current flow or the drift of current carriers under the influence of an electric field. Another type of current flow that is extremely important in transistor work is the diffusion of current carriers when no field is present.

The magnitude of current flow is the net number of charges passing a given cross section of the conductor in a unit time. If the charge carriers are uniformly distributed and move randomly, the average diffusion current is zero, since the number of current carriers moving across a given cross section in one direction is equal to the number moving across the same plane in the opposite direction.

Let us next consider the case in which the charge carriers are not uniformly distributed. Assume that a quantity of charge has been dumped or injected into one end of a crystal as shown in Fig. 1.10. The process by which this is accomplished will be discussed in the next two chapters. The probability that a current carrier near the plane *a-b* will move to the left is equal to the probability that it will move to the right. However, there are more carriers on the left than on the right. Therefore, on the average, more carriers cross the plane from left to right than from right to left. The result is a net flow of current across plane *a-b*. Eventually the current carriers will be uniformly distributed, as shown in Fig. 1.10c. Until this condition exists, diffusion current will flow.



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## Chapter 2

# JUNCTION DIODES

In Chap. 1 we investigated the electrical characteristics of crystals. A junction diode is formed when a piece of N-type semiconductor is joined to a piece of P-type material in such a way that the crystal lattice is continuous across the junction. The electrical characteristics of a diode are radically different from those of either component material. For example, P-type or N-type material will conduct equally well in either direction, but a diode will conduct well in only one direction. This difference is attributed to the nature of the region in the neighborhood of the junction. In this chapter we will focus our attention first on the junction and its characteristics. Then we will treat diodes as circuit elements. Finally, special types of diodes and their applications will be discussed.

The junction diode is an important circuit element. Equally important is the fact that junction diodes are the basic building blocks for almost all semiconductor devices. A good understanding of P-N junctions is necessary in all semiconductor work.

## 2.1. THE POTENTIAL BARRIER

Single crystal P-N junctions may be produced by several processes. Three of the most frequently used methods are:

1. a growing process in which the impurity concentration is varied while a crystal is being "pulled" as grown;
2. an alloying process in which the impurity is melted into a block of semiconductor;
3. a diffusion process in which the impurity gas diffuses into a piece of semiconductor material held at a high temperature.

The process employed determines to some extent the characteristics of a diode. For example, an alloy junction is rather abrupt while a grown



junction is not. Our immediate problem is to develop the theory of the P-N junction. In this development, an abrupt junction will be assumed; therefore, we can expect some minor deviations from the theory for the gradual junctions.

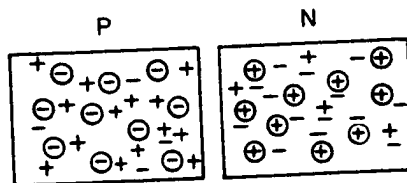


Fig. 2.1. Current carriers in P-type and N-type materials. Note that electrons are majority carriers on the N-side and holes are majority carriers on the P-side. Circles represent charged immobile impurity atoms.

Assume that a block of N-type semiconductor is to be joined to a block of P-type material, as shown in Fig. 2.1, to form a single crystal P-N junction. Prior to the formation of the junction, each block is charge neutral, since each block contains an equal number of free electrons and protons. The N-type material contains a large number of free electrons and an almost equal number of immobile, ionized atoms, each with one plus charge. This block also contains a few holes or minority carriers. In both blocks the product of the majority and minority carriers is  $n_i^2$ , as explained in Chap. 1.

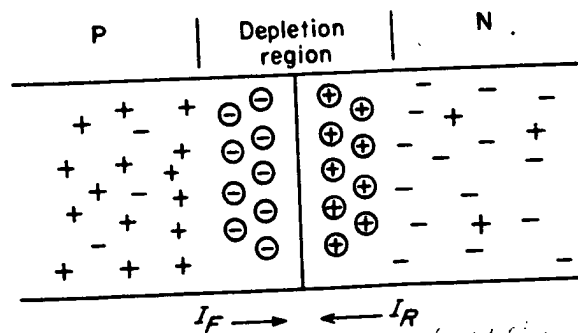


Fig. 2.2. A potential barrier formed at the junction by an array of charged impurity atoms.

When the junction is formed, electrons on the N-side moving to the P-side add to the negative charge on the P-side. A large number of charges (also immobile) are established close to the junction. This action results in a field called the depletion field.

Minority carriers on the N-side are soon swept into the depletion region. Thus, the depletion region contains a large number of majority carriers and a small number of minority carriers.

The potential barrier is uncovered. The potential barrier is uncovered (charge carriers are very few in the depletion region). This action results in a field called the depletion field.

Equilibrium conditions may be:

1. Immobile impurity atoms on the P-side.
2. A field of electrons on the N-side.
3. A voltage across the junction.
4. Majority carriers on the P-side.

\* This potential barrier is for electrons (or Fermi level).

[§2.1]

When the junction is formed, majority carriers on both sides diffuse across the junction. Since each block was initially charge neutral, an electron moving to the P-side leaves a positive ion on the N-side and adds a negative charge to the P-side. In a similar manner, a hole moving into the N-side adds a positive charge to the N-side and leaves a negative charge on the P-side. The net result of this diffusion current is to produce a large number of atoms with positive charges (uncovered impurity atoms) close to the junction on the N-side and an equal number of negative charges (also impurity atoms) on the P-side, as shown in Fig. 2.2. A field is established between the two groups of charges that reduces the diffusion of majority carriers across the junction. The voltage associated with the field is called the *potential barrier*.

Minority carriers on either side of the junction enter the picture as soon as a field is produced. Minority carriers (holes on the N-side or electrons on the P-side) that wander into the field set up by the charged immobile atoms are immediately swept to the other side of the junction. Thus, electrons are forced to move to the N-side, and holes to the P-side. This action reduces the net charge on each side and thereby reduces the magnitude of the potential barrier. The flow of minority carriers across the junction constitutes drift current and is often called *reverse current*,  $I_R$ .

The potential barrier increases in magnitude as more impurity atoms are uncovered on each side of the junction. The region containing these uncovered (charged) atoms is called the *depletion region*, because it contains very few current carriers. As the depletion region extends farther into the material on each side of the junction, more minority carriers are available for reverse current. Finally, a point is reached where the diffusion or forward current is equal in magnitude to the drift or reverse current and equilibrium is established.\*

Equilibrium conditions are shown in Fig. 2.3. Very briefly these conditions may be summarized as follows:

1. Immobile impurity atoms with charges are arrayed on each side of the junction—positive charges on the N-side and negative charges on the P-side.
2. A field exists between these unlike charges.
3. A voltage called the *barrier potential* is associated with this field. The magnitude, under normal conditions, of this voltage is approximately 0.3 volt for germanium and 0.7 volt for silicon.
4. Majority carriers (holes on the P-side and electrons on the N-side) can cross this barrier only if they have energies equal to or greater

\* This process may also be treated in terms of energy. The average energy level or Fermi level of the N-type material is higher than that of the P-material. When the junction is formed, the two energy levels must equalize. This is accomplished by moving electrons into the P-region and holes into the N-region until the average energy levels (or Fermi levels) are equal.

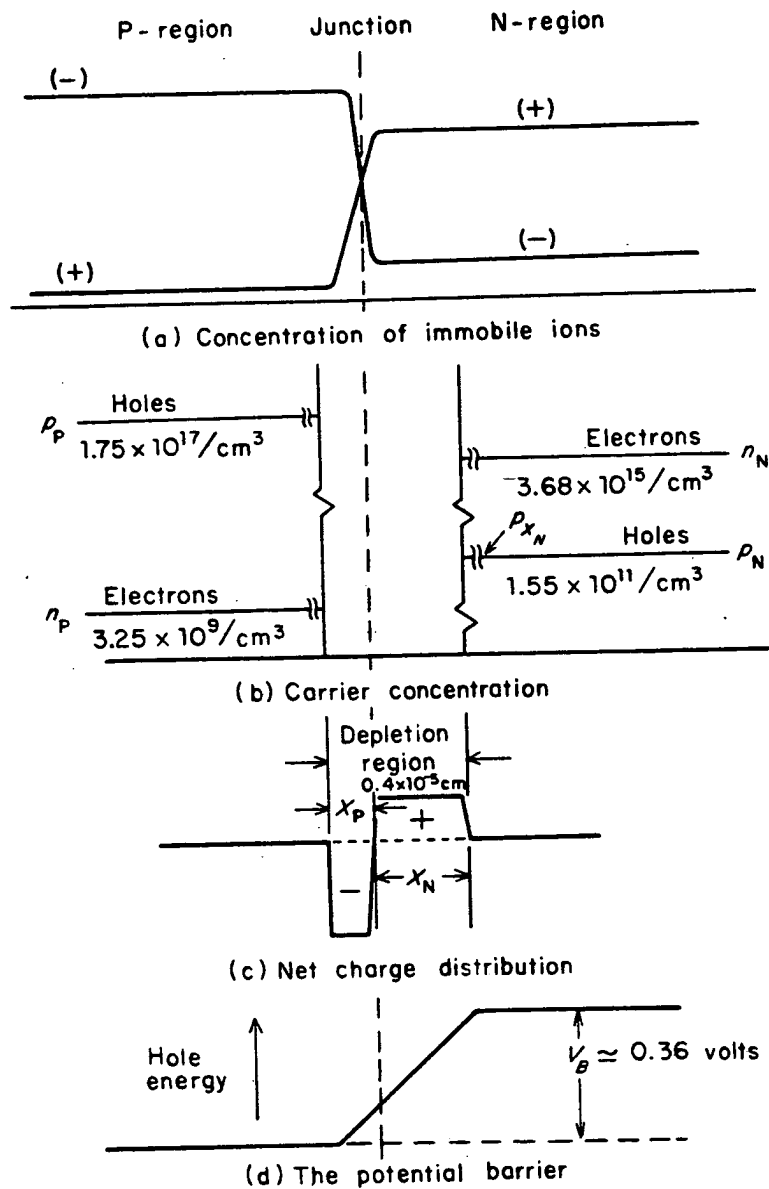


Fig. 2.3. Equilibrium conditions for a typical unbiased diode. (Adapted from *Electronic and Radio Engineering* by F. E. Terman. Copyright, 1955, McGraw-Hill.)

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than 0.3 eV for germanium or 0.7 eV for silicon and are moving in the proper direction.\* Many majority carriers diffuse across the junction.

5. An equal number of minority carriers formed in or near the depletion region are drifting, under the influence of the space charge, in the opposite direction.
6. When an electron (majority carrier) leaves the N-region and moves into the P-region, it becomes a minority carrier. An electron in P-type material does not travel far before it combines with a hole. In a similar manner, a hole moving into the N-side from the P-side quickly combines with an electron. The average distance that minority carriers travel before the total number is reduced to  $1/e$  of the original number is called the *diffusion distance,  $L$* .
7. Regions beyond several diffusion distances from the junction are essentially undisturbed and may be treated simply as N-type or P-type materials.

An equation for finding the value of the potential barrier is

$$V_B = -\frac{kT}{q} \ln \frac{p_N}{p_P} = -\frac{kT}{q} \ln \frac{n_P}{n_N} \quad (2.1)$$

where  $p_N$  is the concentration of holes in the N-region,  $p_P$  is the concentration of holes in the P-region,  $n_P$  is the concentration of electrons in the P-region and  $n_N$  is the concentration of electrons in the N-region.

**Example 2.1.** A germanium diode has  $3.68 \times 10^{15}$  electrons/cm<sup>3</sup> in the N-region and  $1.75 \times 10^{17}$  holes/cm<sup>3</sup> in the P-region. What is the potential barrier across the unbiased junction?

**Solution:** The electron concentration in the P-region is

$$n_P = \frac{n_i^2}{p_P} = \frac{5.76 \times 10^{26}}{1.75 \times 10^{17}} = 3.3 \times 10^9 \text{ electrons/cm}^3$$

$$\text{Then } V_B = -\frac{kT}{q} \ln \frac{n_P}{n_N} = -0.026 \ln (0.896 \times 10^{-6}) = 0.362 \text{ volt}$$

**Problem 2.1.** Find the magnitude of the potential barrier for a silicon diode which is doped one part in  $10^6$  on the P-side and one part in  $5 \times 10^7$  on the N-side. Silicon has  $4.96 \times 10^{23}$  atoms/cm<sup>3</sup>. (Ans. Approx. 0.68 volt.)

**Problem 2.2.** A germanium diode is made of 10 ohm-cm P-type material and 1 ohm-cm N-type material. What is the magnitude of the potential

\* The energy of the moving carrier is  $\frac{1}{2}mv^2$ . The energy associated with the velocity component perpendicular to the barrier must be equal to or larger than the above values.

barrier at room temperature if  $\mu_n$  is 3900 cm<sup>2</sup>/volt-sec and  $\mu_p$  is 1900 cm<sup>2</sup>/volt-sec? [Hint: Assume that the resistivity is controlled solely by majority carriers.]

In a sense, the potential barrier acts as an energy filter or a current equalizer. The potential barrier in the unbiased diode will adjust the forward or diffusion current so that it is equal to the reverse or drift current. If the drift current changes for any reason, the magnitude of the barrier will change, also. For example, an increase in temperature will increase the number of minority carriers generated; therefore, the reverse current will increase. The forward current component will also increase, because more majority carriers have sufficient energy to cross the potential barrier. However, the reverse current increases more than the forward current. In order to equalize the two currents, the potential barrier decreases approximately two millivolts per centigrade degree rise.\* The amount of doping also has an effect on the magnitude of the barrier voltage. Minority carriers must be generated in or near the depletion region to take part in reverse current flow. Decreasing the width of the depletion region will reduce the reverse current and allow the barrier voltage to increase. An increase in the degree of doping decreases the width of the depletion region and increases the barrier potential.

## 2.2. RECTIFICATION

The junction diode is a nonlinear device because it conducts current better in one direction than in the other direction. In the circuit shown in Fig. 2.4 the diode is "forward biased" and will conduct current easily. The battery polarity and the polarity of the potential barrier established within the diode are opposite. Most of the battery voltage is dropped across the junction. The barrier is lowered and the forward or diffusion current increases. If the net potential barrier approaches zero, the diffusion current becomes enormous, and the diode may be destroyed.†

When the battery polarity is reversed in the circuit shown in Fig. 2.4, the diode is "reverse biased." With reverse biasing, the polarities of the potential barrier and the external source are the same. The external voltage raises the potential barrier and decreases the forward or diffusion current. As in the case of a forward bias, virtually all of the external reverse-bias

\* This temperature effect is treated more fully in Chap. 6.

† A forward bias repels majority carriers toward the junction. As these carriers approach the junction, they decrease the width of the depletion region and lower the potential barrier. The increased current resulting from the bias is due almost completely to diffusion. The drift current resulting from the interaction of majority carriers and the voltage source is small and is usually neglected in comparison to the diffusion current.

very practical in that it deals with circuits, component values, and the easiest methods for the solution of real problems."

voltage is dropped beyond about 0.

$$\frac{p_p}{n_p} = \frac{1.7}{3.25 \times 10^4}$$

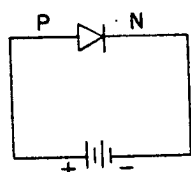
Fig. 2.4. Illustrations for Engineering

As indicated, junction temperature, unbiased junction, concentrations of holes, number of majority carriers of the junction on the opposite edge of the depletion region, P-material is generated, applied to the

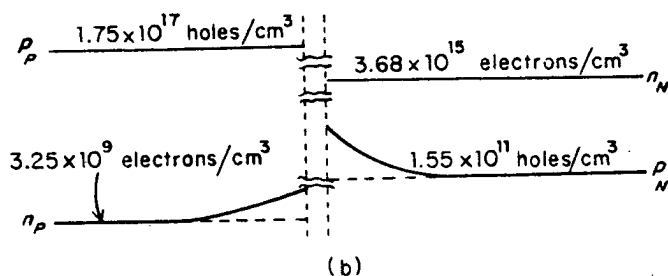
where, as shown

$p_{xN}$  is increased

voltage is dropped across the junction. If the reverse bias is increased beyond about 0.1 volt, the diffusion current is reduced to a negligible value.



(a)



(b)

Fig. 2.4. A forward-biased diode: (a) circuit (b) typical carrier concentrations for a forward-biased diode. (Adapted from *Electronic and Radio Engineering* by F. E. Terman. Copyright, 1955, McGraw-Hill.)

As indicated above, the reverse current is primarily a function of the junction temperature. A comparison of the characteristics of biased and unbiased junctions is shown in Fig. 2.5. If we assume that no recombinations of holes and electrons occur within the depletion region, the same number of majority carriers that enter the depletion region on one side of the junction will emerge as minority carriers from the depleted region on the opposite side of the junction. The hole density (holes/cm<sup>3</sup>) at the edge of the depletion region in the N-material owing to diffusion from the P-material is given by the following equation when no external bias is applied to the diode:

$$p_{X_N} = p_P e^{-qV_B/kT} \quad (2.2)$$

where, as shown in Fig. 2.3,

$p_{X_N}$  is the number of holes per cubic centimeter existing at the edge of the depletion region in the N-material

$X_N$  is the distance that the depletion region extends into the N-material from the junction

$p_P$  is the equilibrium concentration of holes (holes/cm<sup>3</sup>) in the P-material.

With zero external bias, equilibrium exists between the forward and reverse currents in the diode. For this condition we can obtain Eq. (2.3) by altering Eq. (2.2) so that the concentration of holes at  $X_N$  that diffuse

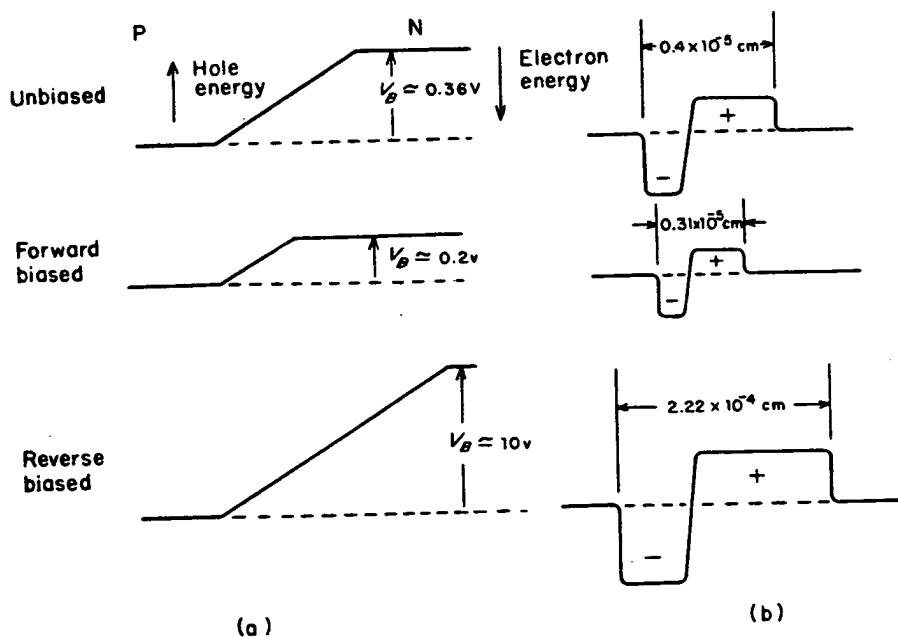


Fig. 2.5. A comparison of typical junction characteristics: (a) potential barrier; (b) charge distribution and depletion regions. (Adapted from *Electronic and Radio Engineering* by F. E. Terman. Copyright, 1955, McGraw-Hill.)

across the junction is equal to the equilibrium concentration of holes existing in the N-material,  $p_N$ , or

$$p_{X_N} = p_P e^{-qV_B/kT} = p_N \quad (2.3)$$

[Notice that Eq. (2.1) may be derived from Eq. (2.3).] If the potential barrier is changed by the addition of an external bias,\* the diffusion current

\* We are assuming that the total bias voltage  $V$  appears across the junction.

[§2.2]

and therefore external bias  $v$

then by using of holes at  $X_N$

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These holes numbers of  $e$  with one of  $t$  proportional to concentration junction is

where  $p_d$  is  $X_N$  is  $L_p$  is

Similarly P-region can diffusion current we see that decreases  $v$  lengths, the value. How that through sion current majority carriers diode are s

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and therefore the concentration of holes at  $X_N$  will change. With an external bias voltage  $V$  applied to the diode,

$$p_{X_N} = p_p e^{q(V - V_B)/kT} = p_p e^{-qV_B/kT} e^{qV/kT}$$

then by using Eq. (2.3) we obtain an equation for the new concentration of holes at  $X_N$ , or

$$p_{X_N} = p_N e^{qV/kT} \quad (2.4)$$

The change in the concentration as a result of the bias is the difference between the total concentration with an external bias and the concentration existing with no bias or

$$\Delta p_{X_N} = p_N (e^{qV/kT} - 1) \quad (2.5)$$

These holes that diffuse across the junction are surrounded by large numbers of electrons. Under this condition, a hole is likely to recombine with one of the electrons and disappear. The recombination rate is proportional to the density of the holes at any point. Mathematically, the concentration of holes  $p_d$  in the N-region at some distance  $d$  from the junction is

$$\Delta p_d = p_N (e^{qV/kT} - 1) e^{(X_N - d)/L_p} \quad (2.6)$$

where  $p_d$  is the concentration of holes at some distance  $d$  into the N-region

$X_N$  is the distance the depletion region extends into the N-region

$L_p$  is the distance at which  $p_d$  equals  $1/e$  of its value at  $X_N$ .

Similarly, the concentration of electrons  $n_d$  at some point  $d$  in the P-region can be determined. Knowing this concentration, we can find the diffusion current at any point in the diode from Eq. (1.4). From Eq. (2.6) we see that the slope of the concentration curve of minority carriers decreases with distance from the junction. After about four diffusion lengths, the minority carrier diffusion current has decreased to a negligible value. However, in a closed circuit, the current is continuous. This means that throughout the diode, the total current is constant, and as the diffusion current due to minority carriers decreases, the drift current of majority carriers increases. The conditions existing in a forward-biased diode are shown in Fig. 2.6.

Diffusion current has a maximum value at the edge of the depletion region, as shown in Fig. 2.6. The magnitudes of the hole diffusion current and the electron diffusion current at the edge of the depleted zone in the N-material and P-material, respectively, are

$$I_{p_{X_N}} = \frac{AqD_p p_N}{L_p} [e^{qV/kT} - 1] \text{ amp} \quad (2.7)$$

and

$$I_{n_{X_P}} = \frac{AqD_n n_P}{L_n} [e^{qV/kT} - 1] \text{ amp} \quad (2.8)$$



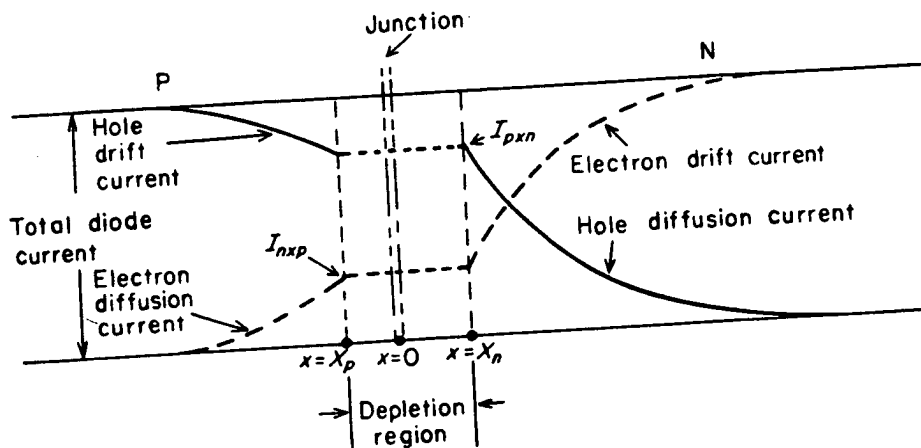


Fig. 2.6. Current components in a forward-biased P-N junction. (Adapted from *Electronic and Radio Engineering* by F. E. Terman. Copyright, 1955, McGraw-Hill.)

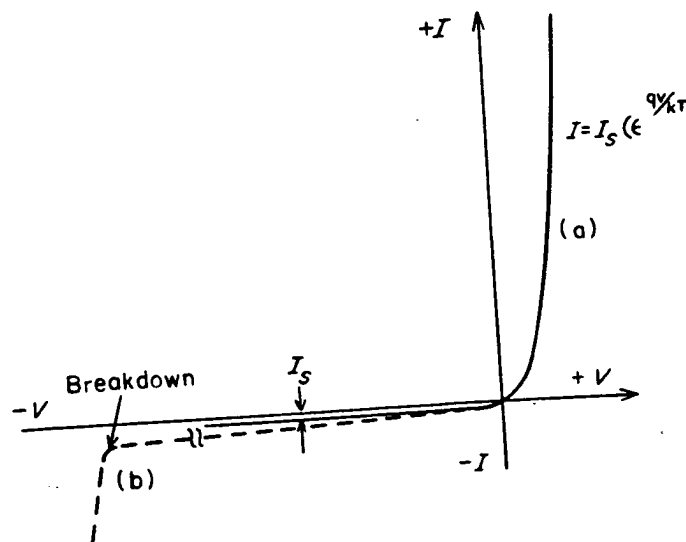


Fig. 2.7. Characteristic curve for a junction diode: (a) theoretical and (b) actual. The actual reverse characteristic curve is different from the predicted theoretical curve because of leakage current and breakdown.

[§2.2]

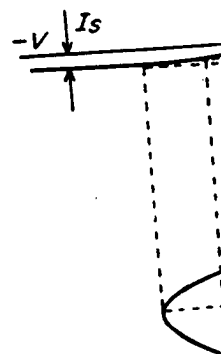
Since the total diode current is the sum of the drift and diffusion currents, the diode current is as follows:

$$I = I_{p_x} + I_{n_x}$$

If the bias voltage is applied, the drift current will be the sum of the diffusion current and the drift current. In addition to Eq. (2.9),

Then we can write

Equation (2.11) is in the form in Fig. 2.7. The actual reverse characteristic curve is different from the predicted theoretical curve because of leakage current and breakdown.



[§2.2]

[§2.2]

# JUNCTION DIODES

35

Since the total diode current is the sum of these two currents, we can write the diode current as a function of bias voltage as.

$$I = I_{p_{x_N}} + I_{n_{x_P}} = qA \left[ \frac{D_p p_N}{L_p} + \frac{D_n n_P}{L_n} \right] (e^{qV/kT} - 1) \quad (2.9)$$

If the bias voltage is made a large negative number (reverse bias), the diffusion current will be reduced to almost zero, and the only current in the diode will be the reverse saturation current  $I_s$ . By applying this condition to Eq. (2.9), the reverse current becomes

$$I_s = Aq \left[ \frac{D_p p_N}{L_p} + \frac{D_n n_P}{L_n} \right] \quad (2.10)$$

Then we can write the expression for the total diode current as

$$I = I_s (e^{qV/kT} - 1) \quad (2.11)$$

Equation (2.11) is the important diode equation and is shown in graphical form in Fig. 2.7. In practice, diodes have characteristics which agree closely with the curve plotted from Eq. (2.11). The only departures from

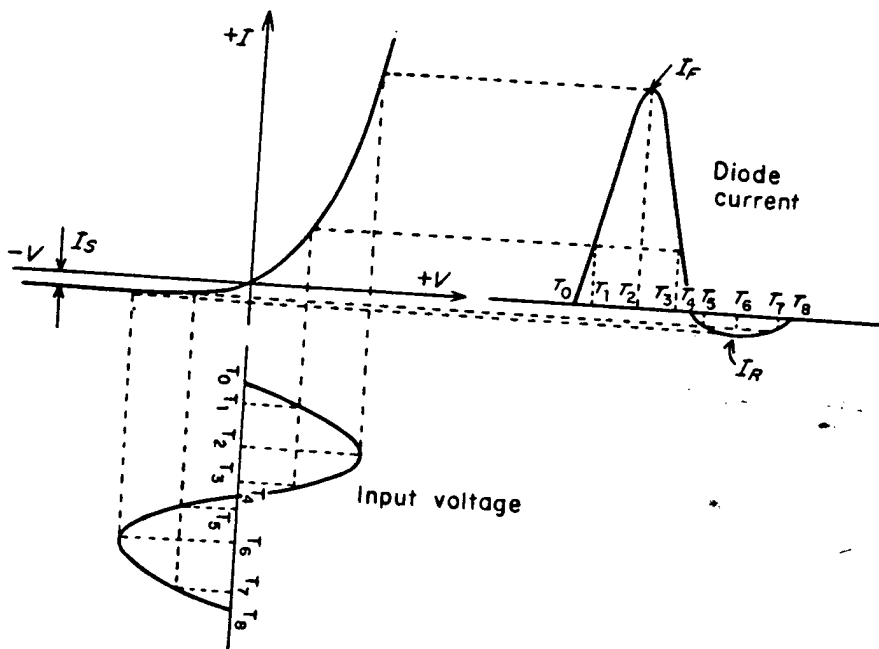


Fig. 2.8. Graphical solution for Ex. 2.2.

the theoretical curve are (a) a slightly increased value of  $I_s$  with reverse bias due to current leakage across the surface of the junction and (b) the phenomenon known as *breakdown* which usually occurs at high reverse voltages.

**Example 2.2.** A germanium diode with a reverse current  $I_s$  of  $5 \mu\text{a}$  has a sine wave applied to its terminals. If the sine wave has a peak amplitude of 0.2 volt, what will be the ratio of the peak forward to the peak reverse currents?

**Solution:** A plot of the performance is shown in Fig. 2.8. The peak forward current occurs at the positive peak of the input voltage. From Eq. (2.11), the peak current is

$$I_F = I_s(e^{qV/kT} - 1) = (5 \times 10^{-6})(e^{39(0.2)} - 1) \\ \approx 12.2 \text{ ma}$$

The current that flows when  $V$  is at its negative peak value is

$$I_R = (5 \times 10^{-6})(e^{-39(0.2)} - 1) \approx 5 \times 10^{-6} \text{ amp}$$

The ratio of the forward to reverse peak currents is

$$I_F/I_R \approx 2440$$

From this example we observe that if the bias voltage exceeds some small value (approximately 0.1 volt), the diode expressions can be simplified to

$$I \approx I_s e^{qV/kT}$$

when  $V$  is greater than +0.1 volt, and

$$I \approx -I_s$$

when  $V$  is less than -0.1 volt.

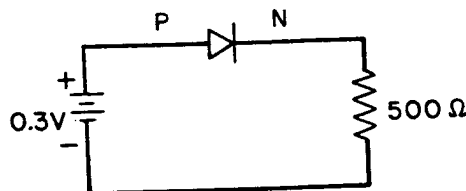


Fig. 2.9. Circuit for Prob. 2.5.

**Problem 2.3**  
volt. Why?  
Ex. 2.2? (A)

**Problem 2.4**  
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**Problem 2.5**  
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## 2.3. ELECTRICAL

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[§2.3]

**Problem 2.3.** Repeat Ex. 2.2 if the peak value of the sine wave is 0.1 volt. Why is the value of the ratio different from that obtained in Ex. 2.2? (*Ans.* Approx. 50)

**Problem 2.4.** Find the maximum and minimum currents that flow in a diode as a function of  $I_s$  if a 0.05-volt-peak sine wave is superimposed on a +0.1 d-c voltage across the diode terminals.

**Problem 2.5.** Find the current that will flow in the circuit of Fig. 2.9 if the reverse diode current  $I_s$  is  $10 \mu\text{a}$  at room temperature. (*Ans.*  $I = 4.08 \times 10^{-4} \text{ a}$ ).

### 2.3. ELECTRICAL CHARACTERISTICS OF DIODES

Diodes are rather complex circuit elements. In this section we will investigate the important electrical characteristics that determine the behavior of the junction diode in a circuit. These characteristics are: (a) forward resistance, (b) reverse resistance, (c) junction capacitance, and (d) speed of response.

#### 2.3.1. Forward Resistance

The nonlinear voltage-current characteristics of a forward-biased diode, as shown in Fig. 2.10, will not allow us to treat it as a fixed value of resistance for different current levels. The static or d-c resistance may be determined graphically by finding the inverse slope (i.e.,  $V_1/I_1$ ) of a line drawn from the origin to a point on the curve corresponding to the d-c current through the diode, as shown in Fig. 2.10. The dynamic or a-c resistance of a diode is also a function of the d-c current through the diode. The a-c resistance may be determined graphically by finding the inverse slope of a line drawn tangent to the curve at the d-c current in the diode. Both the a-c and the d-c forward resistances are rather high for low values of current and decrease in value as the d-c current increases.

If the bulk resistance of a diode is neglected, the a-c and d-c resistance may be obtained analytically. As indicated above, the dynamic resistance may be found from the slope of the diode characteristics. In equation form, this slope is

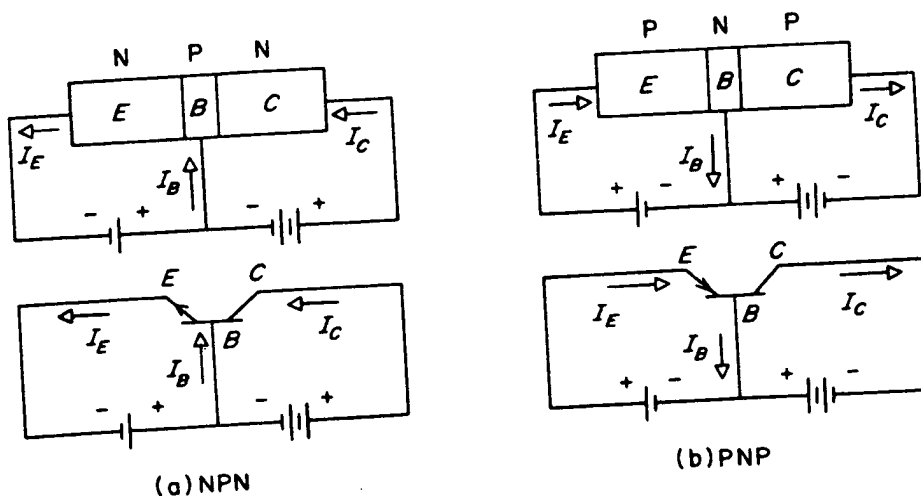
$$r_d = dV/dI \quad (2.12)$$

By taking the derivative of the diode equation (2.11) and inverting the results, the dynamic resistance is obtained. The derivative of Eq. (2.11) is

$$\frac{dI}{dV} = \frac{I_s q}{kT} e^{qV/kT} \approx \frac{qI}{kT} \quad (2.13)$$

# THE JUNCTION TRANSISTOR

Since the characteristics of P-N junctions have already been discussed in Chap. 2, our study of the triode transistor will begin with its d-c operation. After the static characteristics of the device have been determined,



**Fig. 3.1.** Basic-bias-arrangement for (a) an NPN transistor and (b) a PNP transistor. The arrow on the emitter indicates direction of conventional current flow in either case.

its operation as an arm  
the different types of tr  
will be discussed.

Both NPN and PNP transistors have the appropriate bias (the emitter junction is biased in forward bias (negative voltage) whereas the collector junction is reverse-biased (increasing the barrier height). The barrier is very small, and both electrons and holes are more heavily doped in the emitter. Electrons are the more important carriers in NPN transistors, and holes are the important carriers in PNP transistors.

The external collector voltage to 10 volts is typical across the collector-emitter junction. The collector-base voltage is the sum of the emitter-base voltage.

As explained in the junction that the barrier. In di was called the re called the collect the bottom curve base connection, reasons: (a) all of the minimum cu bias conditions. volt, very few m resulting barrier with the emitter  $V_{CB} = 0$  and sat until breakdown

its operation as an amplifier will be considered briefly. Finally, some of the different types of transistors and the differences in their characteristics will be discussed.

### 3.1. STATIC CHARACTERISTICS

Both NPN and PNP junction transistors are shown in Fig. 3.1 with the appropriate bias polarities. Note that in both cases, the emitter-to-base junction is biased in the forward direction (the bias reducing the barrier voltage) whereas the collector-to-base junction is reverse biased (the bias increasing the barrier voltage). The physical thickness of both bases is very small, and both are lightly doped. The emitters and the collectors are more heavily doped. A major difference between the two units is that holes are the more important carriers for PNP transistors, whereas electrons are the important carriers for NPN transistors.

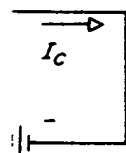
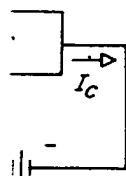
Let us now study the operation of an NPN transistor, keeping in mind that a PNP unit operates in the same manner but with the role of electrons and holes reversed. When the emitter circuit is open, no emitter current can flow. The emitter-to-base junction potential is approximately the same as that of the unbiased potential barrier. Therefore, the forward current  $I_F$  equals the reverse current  $I_R$  across this junction.

The external collector bias may have a magnitude of several volts (5 to 10 volts is typical). Virtually all of this external voltage is dropped across the collector-to-base junction. The polarity is the same as that of the collector-base potential barrier. The total voltage across the junction is the sum of the unbiased barrier voltage and the external collector-to-base voltage.

As explained in the diode discussion, minority carriers on each side of the junction that diffuse into the resulting electric field will be swept across the barrier. In diodes this flow of minority carriers across the junction was called the *reverse saturation current*  $I_S$ , but in transistor work it is called the *collector cutoff current*  $I_{CO}$  or  $I_{CBO}$ . The  $I_{CO}$  current constitutes the bottom curve on a set of output characteristic curves for the common-base connection, as shown in Fig. 3.2a. This curve is important for two reasons: (a) all of the other curves are referenced to it, and (b) it indicates the minimum current that will flow in the collector circuit under normal bias conditions. When the collector voltage exceeds approximately 0.1 volt, very few majority carriers on either side of the junction can cross the resulting barrier, because they do not have sufficient energy. Therefore, with the emitter circuit open, the collector current starts from zero for  $V_{CB} = 0$  and saturates at  $I_S$  or  $I_{CO}$  for values of  $V_{CB}$  greater than 0.1 volt until breakdown or carrier multiplication occurs.

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The second curve shown in Fig. 3.2a is the output characteristic generated when a fixed amount of emitter current is allowed to flow. Emitter current flows when the emitter circuit is closed and the unbiased potential barrier is reduced with an external bias voltage. From our diode discussion we know that under forward-bias conditions, the forward current  $I_F$  increases and the reverse current  $I_R$  remains relatively constant.

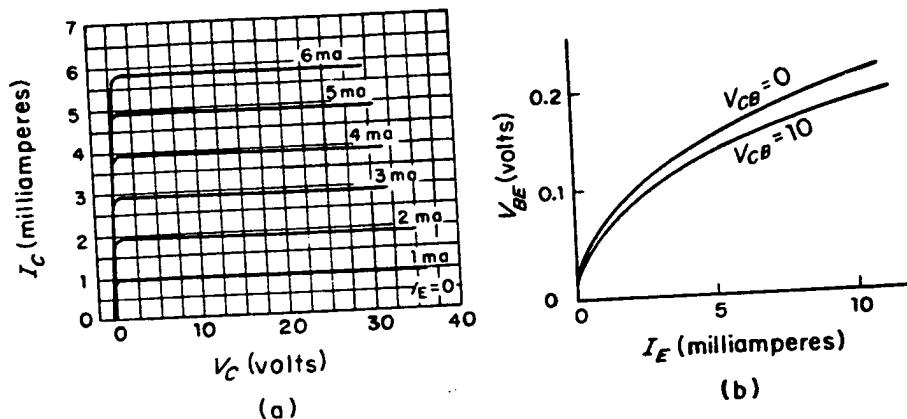


Fig. 3.2. Static characteristics for the NPN common-base connection: (a) output characteristics and (b) input characteristics.

As a result, majority carrier flow exceeds minority carrier flow. For an NPN transistor this means a net flow of electrons from the emitter into the base and a net flow of holes from the base into the emitter. Since the degree of doping in the base is much lighter than that for the emitter, the current across the junction is due largely to electron flow (hole flow for a PNP transistor).

Electrons that move from the emitter into the base would combine with holes in the base if the base thickness exceeded several diffusion lengths. By making this thickness much less than one minority carrier diffusion distance, we can cause many electrons to diffuse through the thin base into the base-collector depletion region. All electrons that reach this region are quickly swept into the collector. Once in the collector, they diffuse to the collector terminal and move into the metallic circuit. Two points should be emphasized: (a) the emitter-to-base bias essentially determines the magnitude of the emitter current, and (b) the base thickness and degree of doping effectively determine how many of the current carriers from the emitter diffuse through the base and reach the collector. In a good transistor only a very small percentage of the minority current carriers is captured in the base region. Therefore, most of the carriers

[§3.1]

from the emitter reach the collector. The emitter current is almost the same amount as the collector current.

The ratio of a carrier's drift velocity to the diffusion velocity is defined as  $\alpha$ , or

This ratio is usually called the transport factor.

Considering only the emitter, the transport factor is the ratio of the emitter current to the collector current. If the thickness of the emitter is small compared to the diffusion length, a very small percentage of the emitter current recombines in the emitter. The good transistor 90% of the emitter current gives a transport factor of 0.90.

Our diode study shows that most of the majority carriers injected into the emitter recombine in the emitter. We have considered the NPN transistor, but the same principles apply to the PNP transistor.

The collector current is the base-collector current multiplied by the base-emitter current. This produces a noticeable collector-to-base current. To account for this efficiency as the ratio of collector current to emitter current, efficiency is defined as  $\alpha$ .

For higher collector efficiency is defined as  $\alpha$ .

[§3.1]

from the emitter reach the collector. If the emitter-to-base bias is increased, the emitter current is also increased, and the collector current increases by almost the same amount. This relationship is shown graphically in Fig. 3.2a.

The ratio of a change in collector current to a change in emitter current is defined as  $\alpha$ , or

$$\alpha \equiv \Delta I_C / \Delta I_E \mid \Delta V_C = \text{const.} \quad (3.1)$$

This ratio is usually close to unity and is determined by three factors: (a) a transport factor, (b) an emitter efficiency, and (c) a collector efficiency.

Considering only those carriers that are injected into the base from the emitter, the *transport factor* indicates the percentage that reaches the collector. If the thickness of the base region is much less than one diffusion length, a very small percentage of the carriers is captured in the base (volume recombination) as they diffuse to the collector junction. Another small percentage, determined by the transistor geometry, diffuses to the outside edge of the base and is lost through surface recombination. In a good transistor 90 per cent or more of these carriers reaches the collector, giving a transport factor of 0.90 or greater. Those carriers lost in the base region either by volume recombination or by surface recombination become part of the base current.

Our diode study indicated that when the barrier voltage is lowered, majority carriers on both sides of the junction diffuse across the junction. We have considered only those moving from the emitter to the base. In an NPN transistor, holes from the base (base majority carriers) will cross the junction into the emitter. These holes originate at the base terminal and recombine in the emitter. They increase the emitter current but not the collector current. The *emitter efficiency* indicates the fractional part of the emitter current that is made up of emitter majority carriers being injected into the base. This number is usually very close to unity and can be increased by decreasing the doping density in the base region.

The collector current may be greater than that predicted from the transport factor. This increase is due, in part, to carrier multiplication in the base-collector depletion region. As explained in our diode discussion, carrier multiplication occurs when one carrier ionizes one or more atoms and produces additional carriers in the depletion region. This effect is not noticeable for low collector voltages, but it may become significant as the collector-to-base voltage increases. The additional carriers generated in this manner, like thermally generated carriers, add to the collector current. To account for this increase in collector current, we define *collector efficiency* as the ratio of the total collector current to the current composed of carriers from the emitter. For low collector voltages, the collector efficiency is essentially unity and may increase to values greater than unity for higher collector voltages.



The value of  $\alpha$  may be obtained by finding the product of the three factors discussed above. Good transistors have values of  $\alpha$  above 0.90, and values above 0.99 are not unusual. The transport factor and  $\alpha$  usually have approximately the same value. In order to simplify our immediate discussion, we will assume that the transport factor and  $\alpha$  are equal. Then the transistor d-c currents are:

$$(a) \quad \text{emitter current} = I_E \quad (3.2)$$

$$(b) \quad \text{base current} = (1 - \alpha)I_E - I_{CO} \quad (3.3)$$

$$(c) \quad \text{collector current} = \alpha I_E + I_{CO} \quad (3.4)$$

**Example 3.1.** A type 2N43 transistor has an  $\alpha$  of 0.98 and an  $I_{CO}$  of  $10 \mu\text{a}$ . Find the base and collector currents when the emitter  $I_E$  is 1 ma.

*Solution:* The collector current is

$$\begin{aligned} I_C &= 0.98 \times 1 \text{ ma} + 10 \mu\text{a} \\ &= (980 + 10)\mu\text{a} = 990 \mu\text{a} = 0.99 \text{ ma} \end{aligned}$$

The base current is

$$\begin{aligned} I_B &= (1 - 0.98)(1 \text{ ma}) - 10 \mu\text{a} \\ &= (20 - 10)\mu\text{a} = 10 \mu\text{a} \end{aligned}$$

Note that the collector and emitter d-c currents are almost equal.

A study of the static-output characteristic curves for the common base (CB) connection reveals several interesting points.

1. The collector current and the emitter current are approximately equal over almost the entire operating range.
2. The spacing between adjacent curves is almost constant, indicating that  $\alpha$  changes very little with variations in collector voltage.
3. The spacing between curves does not change drastically for different values of  $I_C$ , indicating that  $\alpha$  is relatively constant with changes in  $I_C$ .
4. The collector current is not zero when  $I_E$  is zero but has a value of  $I_{CO}$ . Most silicon transistors and many germanium units have  $I_{CO}$  values of less than  $1 \mu\text{a}$  at room temperature.
5. All curves have a slight positive slope due, in part, to the current multiplication effects in the collector junction.
6. For low-emitter currents,  $I_C$  does not reach zero for  $V_C = 0$ . In order to reduce  $I_C$  to zero, the collector voltage must be reversed.

The input curves for the CB connection are very nonlinear. These

curves are effectively modified slightly. collector voltage reduces the effect in a thinner base collector-to-base.

Fig. 3  
config

In the common base is an input output characteristic

If  $\alpha$  were to be obtained and (3.4) shown. With CB curves following

## TRANSISTOR THEORY

A professional approach is taken. This accurate value of your book, very practical circuits, common methods for

[§3.1]

curves are effectively determined by the emitter-to-base diode characteristic, modified slightly by the effect of the collector voltage. An increase in the collector voltage produces a wider base-to-collector depletion region and reduces the effective width of the base. Fewer stored charges are required in a thinner base. Therefore, the emitter current increases when an external collector-to-base reverse-bias voltage is applied.

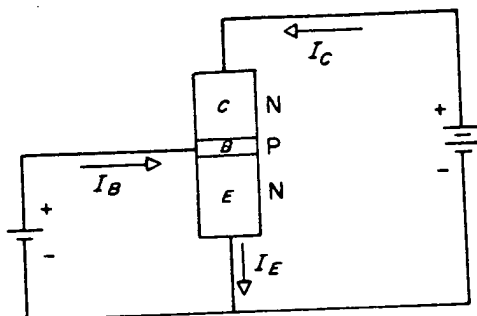


Fig. 3.3. Bias arrangement for a NPN transistor connected in the CE configuration.

In the common-emitter (CE) circuit, shown in Fig. 3.3, the base current is an input variable and is usually the running variable for the static-output characteristic curves. As indicated above, the base current is

$$I_B = (1 - \alpha)I_E - I_{CO}$$

If  $\alpha$  were absolutely constant, the output curves for the CE circuit could be obtained from the output curves of the CB connection and Eqs. (3.3) and (3.4). Small variations in  $\alpha$  do occur over the ranges of  $I_C$  and  $V_{CE}$  shown. While a change of one or two percent in  $\alpha$  is not noticeable on the CB curves, a large change is apparent in the CE case, as indicated in the following example.

**Example 3.2.** A transistor has an  $\alpha$  of 0.98 and an  $I_{CO}$  current of  $5 \mu\text{A}$  when  $I_E$  is 1 ma and  $V_{CE}$  is 6 volts. When  $V_{CE}$  is increased to 12 volts and  $I_E$  remains at 1 ma,  $\alpha$  increases to 0.99. Find the measured base-current values for the two cases.

**Solution:**

$$(a) \quad I_B = (1 - 0.98)1 \text{ ma} - 5 \mu\text{A} = 15 \mu\text{A}$$

$$(b) \quad I_B = (1 - 0.99)1 \text{ ma} - 5 \mu\text{A} = 5 \mu\text{A}$$

An increase of approximately one per cent in  $\alpha$  reduces the base current to one-third of its initial value. From this example, we see that the spacing between adjacent base-current curves is very sensitive to changes in  $\alpha$ .

**Problem 3.1.** Find the collector current corresponding to zero base current for each of the conditions in Ex. 3.2. (Ans. (a) 0.245 ma)

Neither  $\alpha$  nor  $I_{CO}$  remains absolutely constant over the working range of  $I_C$  and  $V_{CE}$ .  $I_{CO}$  increases with an increase in  $V_{CE}$ , causing the curves of constant base current in Fig. 3.4 to have an appreciable positive slope.

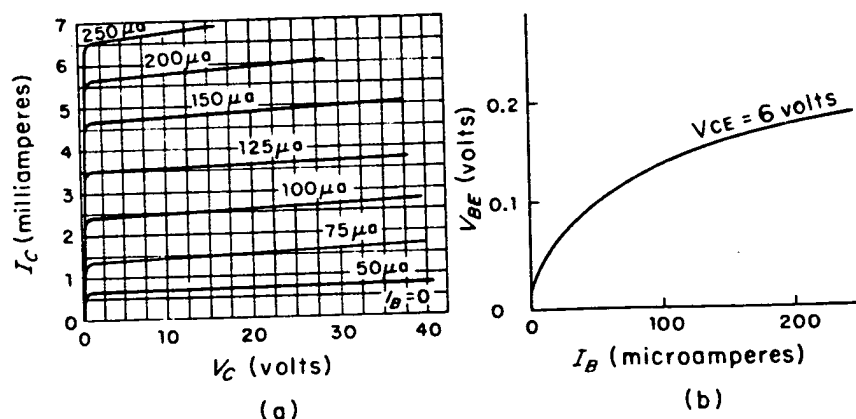


Fig. 3.4. NPN common-emitter static characteristics: (a) output characteristics and (b) input characteristics.

Changes in  $\alpha$  produced by an increase\* in emitter (or collector) current cause the distance between adjacent current curves to vary. Defining the current gain for the CE configuration as  $\beta$ , we have

$$\beta = \left. \frac{\Delta I_C}{\Delta I_B} \right|_{V_{CE} \text{ const}} \quad (3.5)$$

By comparing the two sets of output characteristics, we observe that the value of  $\beta$  is much larger (20 to 200 times larger) than  $\alpha$  and is also much

\* The transport factor depends upon the ratio of the number of majority carriers in the emitter to the number of minority carriers in the base. In an NPN transistor, this ratio is  $n_N/n_P$ . As the transistor current increases, the number of stored charges in the base increases, causing this ratio (and therefore the transport factor) to decrease. When the transport factor decreases,  $\alpha$  decreases.

[§3.2]

more dependent on  $t$  and (3.4), the relation

Assuming that  $\alpha$  is constant, the CE curves shown in Fig. 3.4 are different. Only the spacing of curves are different, not true.

**Example 3.2** when  $V_C = 125 \mu A$ .

**Solution:** Find

**Problem 3.2** 100, find the (Ans. (a) 50

**Problem 3.2** perature, re change with

### 3.2. TRANSISTOR

The two sets of design work and : These curves may equations governing these equations with

Since the emitter either can emit or be different, and physically than the collector must discharge, collector is much more,  $\alpha$ ) is closer to

[§3.2]

more dependent on the operating current and voltage. From Eqs. (3.3) and (3.4), the relationship between  $\alpha$  and  $\beta$  is

$$\beta = \alpha / (1 - \alpha) \quad (3.6)$$

Assuming that  $\alpha$  is constant and neglecting  $I_{CO}$ , we find that the input CE curves shown in Fig. 3.4 have the same shape as those for the CB connection. Only the current scale is different. The shapes of the two sets of curves are different only to the extent that these two assumptions are not true.

**Example 3.3.** Estimate the value of  $\beta$  from the curves in Fig. 3.4 when  $V_C = 15$  volts and the base current varies from  $100 \mu\text{a}$  to  $125 \mu\text{a}$ .

*Solution:* From the curves,

$$\Delta I_C = 3.6 - 2.5 = 1.1 \text{ ma}$$

From the data given,

$$\Delta I_B = 125 - 100 = 25 \mu\text{a}$$

$$\beta = 1100/25 = 44$$

**Problem 3.2.** A transistor has an  $I_{CO}$  current of  $0.5 \mu\text{a}$  at  $30^\circ \text{C}$ . If  $\beta$  is 100, find the collector current (a) when  $I_B = 0$  and (b) when  $I_B = 50 \mu\text{a}$ .  
(Ans. (a)  $50 \mu\text{a}$ )

**Problem 3.3.** If  $I_{CO}$  doubles for each 10 centigrade degrees rise in temperature, repeat Prob. 3.2 for a temperature of  $60^\circ \text{C}$ . How does  $I_C$  change with a rise in temperature when  $I_B$  is held constant?

### 3.2. TRANSISTOR EQUATIONS

The two sets of curves shown in Figs. 3.2 and 3.4 are very useful for design work and are usually available from manufacturers' data sheets. These curves may be generated (approximately) with a set of symmetrical equations governing the performance of triode transistors. A study of these equations will yield further insight into the operation of a transistor.

Since the emitter and the collector both have the same type of doping, either can emit or collect. In practice, however, the degree of doping may be different, and the collector is usually (but not always) much larger physically than the emitter for two reasons. First, in the usual case, the collector must dissipate more power than the emitter. Second, when the collector is much larger than the emitter, the transport ratio (and, therefore,  $\alpha$ ) is closer to unity. The latter effect is shown in Fig. 3.5. Minority

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